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GAS CONTROL AND WALL CONDITIONING IN TMX*

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Abstract

The Tandem Mirror Experiment (TMX) is a magnetic fusion research device at the Lawrence Livermore Laboratory, which confines a center-cell plasma between two higher density end-plug plasmas. The end-plug plasmas are separated from the metal end walls by an end-fan chamber. This paper describes how we minimize the power lost through charge-exchange and electron conduction. To isolate the end-plug plasma from the end wall, we employ wall conditioning, gas pumping, and magnetic-field expansion in the end-fan chamber. The plasma density is reduced from above $10^{13} cm^{-3}$ in the end-plug to well below $10^{10} cm^{-3}$ at the end wall. A peak plasma potential of more than 1 kV above the grounded end wall is maintained in steady-state and gas buildup near the end wall is avoided. Gas flow in the end plug is controlled and the end-plug walls are conditioned so that the end-plug plasma is not eroded by large fluxes of cold gas. Wall conditioning in the center cell provides reproducible conditions. The center cell is fueled by gas from a gas box or a pulsed valve.

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1. Introduction

The Tandem Mirror Experiment (TMX) [1] is a magnetic-fusion research device which has demonstrated electrostatic end-plugging of a magnetic-mirror confined plasma. A schematic of TMX is shown in fig. 1. The end-fan chamber in TMX must absorb the axial losses and isolate the plasma from the end wall. TMX requires the end-plug plasma potential to be above 1 kV and the electron temperature to be roughly 200 eV, so the electron conduction and power flow to the end wall must be sufficiently small. Plasma buildup in the end-fan due to gas production or arcing at the end wall can enhance the power flow to the end walls [2], cool the mirror-confined plasma, and reduce the plasma potential. In TMX, ion currents of order 10^{21} ions s^{-1} must be pumped in the end-fan chamber. The end-plug plasmas are fueled by neutral beams and are confined in minimum-B magnetic fields, as was the plasma in the conventional mirror machine, 2XIIB [3]. Gas that impinges on the end-plug plasma can remove the energetic ions by charge exchange. As in 2XIIB, control of the flow of gas introduced by the neutral-beam system is necessary to minimize these losses, as is conditioning of the surfaces bombarded by the neutral beams [4]. The center-cell of TMX must contain and fuel the center-cell plasma. Wall reflux and gas production must be controlled to avoid undesired gas buildup and to minimize the power lost to the radial walls of the plasma chamber. These needs are provided by wall conditioning and gas injection using a pulsed valve or a gas box.

This paper describes how we minimize the power lost by electron conduction to the end wall and by charge-exchange of the plasma ions on D_2 gas. The TMX plasma and gas sources are described in Section 2. Sections 3, 4, and 5 discuss the end-fan chamber, the end-plugs, and the center-cell. Section 6 is a summary.

were designed to reduce the plasma density at the end wall, the buildup of gas and cold plasma in the end-fan chamber, and the transport of energy to the end wall by the electrons. These goals have been met as described below.

The plasma density at the end wall of TMX is $\sim 2 \times 10^9\ cm^{-3}$, during a characteristic steady state, as measured using an x-band interferometer [5]. A gridded end-loss analyzer measures the energy spectrum of the end-loss ions. The end-wall plasma density is bounded by the end-loss analyzer data to be below $6 \times 10^9\ cm^{-3}$. The end-loss analyzer, the x-band interferometer, and ion-saturation current detectors observe similar time evolution of the plasma in the end fan (fig. 6). Some cold plasma may be present as a result of wall recycling; but these diagnostics indicate that the cold plasma does not accumulate. A fast ionization gauge at the end wall of TMX shows that the pressure remains below 3.0×10^{-5} torr. This is consistent with the neutral gas production expected at the end wall and the pumping speed of the chamber. In 2XIIB, the plasma density at the end wall was above $10^{12} cm^{-3}$ [6]. Thus we have reduced the plasma density at the end wall three orders of magnitude in TMX by comparison with 2XIIB, for similar plasma densities within the mirror cell.

If a mirror-confined plasma is well isolated from the end wall, most of the power reaching the end wall will be carried by the ions rather than the electrons. This is because the ions are accelerated by the electric potential of the plasma ($e\phi \sim 10\ KT_e$) when they escape the plasma, but the electrons are decelerated and only carry an average of one unit of electron temperature ($\sim KT_e$) to the wall.

In contrast, secondary-electron emission and/or plasma buildup at the end wall can enhance the electron power striking the wall and reduce the plasma potential. In TMX, the ions deliver most of the power reaching the

2. TMX plasma and gas sources

The end-plug plasmas in TMX reach central densities of 1 to 4 x 10^{13} cm^{-3}, electron temperatures up to 270 eV, plasma potentials above 1 kV, and mean ion energies near 10 keV. The neutral beams have injected up to 200A of equivalent atom current of deuterium into each end plug, with a mean energy of 13 keV for a duration of 25 ms. The D_2 (deuterium) gas flow from the neutral-beam modules into each end tank is roughly 400 torr-l-s^{-1} for $\sim$ 60 ms.

The center-cell plasma is maintained at a lower density than the end-plug plasmas ($\sim 5 \times 10^{12}$ cm^{-3}) so that the center-cell ions are confined by an electrostatic potential well (100 to 300 volts deep). At the core of the center-cell plasma, the ion energies are 80 to 180 eV. This plasma is fueled by roughly 150 torr-l-s^{-1} of deuterium gas; penetration of the gas into the plasma depends upon multiple charge-exchange interactions.

The end-fan plasmas in TMX are established by the end losses from the center-cell and the end plugs. No gas is ordinarily introduced into the end-fan chamber, and there is little buildup of gas or low-energy plasma (see below). The ions escaping from the central core of the TMX plasma have a density of order $10^9 cm^{-3}$ at the end wall and strike the wall with mean energies above 1 keV.

3. The TMX end-fan

The TMX end-fan chambers differ from the chambers in 2XIIB 3 . The volume of each end-fan chamber is 16,000 liters, compared to 3700 liters in 2XIIB. The liquid-nitrogen-cooled surface area in each TMX chamber is 26 m^2, and all the walls are gettered by titanium evaporation. The end-wall field in TMX is $\sim$ 70 Gauss, in 2XIIB it was 2 kG. The TMX chambers end wall. The total power ($\sim 4\ W/cm^2$), as measured by a calorimeter, agrees with the power delivered by the ions, as measured by the end-loss analyzer [7]. In 2XIIB, similar measurements indicated that the electrons delivered most of the power to the end wall [10]. We conclude that the improved pumping and reduced density in the TMX end-fan, compared to 2XIIB, have in this respect improved the performance of TMX. The higher electron temperatures obtained in the TMX end plug [1] may be a consequence of these changes.

Finally, the end-fan chamber in TMX electrically isolates the plasma from the end wall, so that a plasma potential above 1 kV is maintained. We have measured end-loss spectra which showed minimum ion energies above 1 keV. That is, the measurable ion current striking the end wall was entirely composed of ions with at least 1 keV of energy. This current is known to originate in the TMX center cell, because the neutral-beam current ionized in the end plug is small by comparison with the gas ionized in the center cell and with the magnitude of the observed end losses. Thus, we can produce plasmas with potentials above 1 keV. These high-voltage plasmas are connected along magnetic field lines to a grounded surface. Destructive arcing, which would short out the voltage, is not present.

4. The TMX end plugs

The D_2 gas introduced into the TMX end tanks must be prevented from reaching the plasma. Of the 200 A of energetic atom current injected by the neutral beams, only 20 A ($\sim$2t-l-s^{-1}) is ionized in the end-plug plasma. To avoid erosion of the end-plug plasma by charge exchange, the energetic ions must be allowed to pump no more than 2 of the 400 torr-l-s^{-1} introduced by the neutral beam system. To satisfy this requirement, the D_2 pressure in the plasma chamber must not exceed a few times 10^{-5}

torr. Somewhat more gas can strike the plasma if a "plasma shield" is present [9]. We use baffles, gettering, and liquid-nitrogen-cooled surfaces to maintain a low D_2 pressure in the end plug [10].

Baffles in TMX divide the end tanks into several pumping regions. The volume of each end tank is roughly 60,000 liters, including the 16,000 liters end-fan chamber and the dome attached to the center cell. Each end tank contains titanium-gettered panels which can be cooled by liquid nitrogen. The gettered and cooled surface area is 145 m^2 per end tank. These panels baffle the end tank into an outer annulus, an inner annulus, and an end-fan chamber. The end-plug magnets separate the plasma chamber from the inner annulus and the end-fan chamber. The pumping surfaces in the end tank are covered with a few monolayers of titanium before the plasma shot every one to three shots. The titanium is deposited by evaporation from 0.32-cm diameter titanium-alloy wire (85 wt.%Ti - 15 wt.%Ta). There are 88 wires distributed throughout TMX. The effects of these baffles, and of titanium gettering, are shown in fig. 2. Gas was injected into the TMX vacuum chamber through a neutral beam. Before gettering, the D_2 pressure rises highest in the outer annulus and slowly reaches an equilibrium as the gas flows into other parts of the machine, fig. 2a.

The gas flow was modeled using a computer code, and the results are shown in fig. 2. The code reproduces the qualitative behavior of the data. The quantitative differences seen in the figure are believed to result from uncertainties in the conductances and volumes used in the code. The effect of gettering is illustrated in fig. 2b. After a pumpdown and before gettering, the upper trace was observed in the end-fan chamber. After gettering, the pressure remains lower and reaches equilibrium faster than it does before gettering. The lower trace in fig. 2b shows this effect. The computer code reproduces these results as shown, using a sticking coefficient of 0.03.

When the panels are cooled by liquid nitrogen, the pumping speed of the system increases. The decrease in maximum pressure and increased response time for the same gas input are shown in fig. 3. With the use of liquid nitrogen cooling, the gas introduced by the neutral-beam system is pumped and the gas impinging on the plasma from this source becomes acceptably small.

Gas can also be desorbed from the surfaces bombarded by the neutral beams, or by charge-exchange products from the plasmas, or by ultraviolet radiation. When TMX has been vented to air for maintenance, substantial gettering and neutral-beam operation is needed to obtain plasmas which do not decay prematurely. Figure 4 shows a characteristic progression from a 5 ms duration to a 20 ms duration (the maximum requested by the control system for this data). The plasma duration was quite sensitive to the energetic neutral-beam current during this run; shots with lower beam were shorter. Gas desorbtion is believed to be responsible for these observations, and for similar trends observed in 2XIIB. Once full-duration plasmas have been attained, the operating characteristics of the end-plug plasmas do not change significantly until TMX is again vented to air. Gettering alone did not enable us to produce full-duration plasmas, but in one case, after gettering and continual neutral-beam operation, the end-plug plasma did not require the conditioning shots described above. In the near future, we intend to attempt glow-discharge cleaning to reduce the amounts of machine operation required to condition the walls.

5. The TMX center cell

The center-cell vacuum chamber is separated from the end-plug chambers by disc-shaped baffles. These baffles prevent the flow of gas between the two regions. The center-cell volume is 23,500 liters. The center-cell walls are at room temperature, and are covered with titanium evaporated from getter wires. Their surface area is 78 m^2. The center-cell walls are gettered to provide a reproducible surface that does not evolve gas. When the center-cell plasma is fueled by the gas boxes (see below) the pressure remains below 5.0×10^{-6} torr. At this pressure the flux of D_2 gas impinging on the plasma is negligible by comparison with the gas feed.

The center cell may be fueled either by gas boxes or by a pulsed valve (gas puffer). The gas boxes are located where the plasma cross-section is very elliptical. These boxes are essentially two limiters with gas valves between them. Gas introduced into the gas boxes is very likely to be ionized before it can escape from the gas box. The gas puffer injects gas near the midplane of the center cell vacuum chamber. Most of the gas is pumped by the plasma, as illustrated in fig. 5. The pressure declines slowly while the plasma is present and increases once the plasma has decayed. If no plasma is produced, the pressure rises monotonically.

6. Summary

Gas control and wall conditioning in TMX have been described. Neutral-beam-fueled end plug plasmas, a steady-state center-cell plasma, and a plasma potential above 1 kV can be maintained. Significant accumulation of gas or cold plasma in the plasma-surface regions has been avoided. In the future, we expect to use surface probe diagnostics in collaboration with Sandia Laboratories, and to perform other experiments to further investigate plasma surface interactions in TMX.

Acknowledgements

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Figure Captions

1. Schematic TMX. The plasmas gas sources and differential-pumping system are shown.

2. Measurements and modeling of the gas flow in TMX. The solid lines show the measured pressure change during and after a 55 ms injection of D_2 gas using a pulsed valve in one neutral-beam module. After pumpdown but before gettering, the effect of the baffles is observed (a). Gettering significantly changes the system response, as illustrated by data obtained in the end-fan chamber (b). Dashed lines show the results of computer modeling.

3. The effect of the LN-cooled panels on pumping in two volumes of TMX. The upper traces show the measured pressure change during and after a 60 ms pulse of gas from eight neutral beam modules, with gettered room temperature walls. After the LN panels are cooled, the pressure rise is less and the gas is pumped more quickly.

4. The duration of the TMX plasma is shown as a function of number of plasma shots attempted after a vent.

5. The D_2 pressure in the center-cell chamber is shown as a function of time. The effect of a plasma on this pressure is shown. The gas flow into the chamber was 270 torr-l-s^{-1}, and the gas puffer was fired at -5 ms.

6. Measurements of the TMX end-fan plasma. Plasma guns are fired in the end-fan chamber from 5 to 10 ms; a steady state is achieved from 11 to 20 ms; and at 20 ms the neutral beams fueling the nearest end-plug plasma are turned off and that plasma decays. During steady state, the end-loss analyzer and a probe biased into ion saturation detect similar currents. Sheath effects may explain the differences early and late in the shot. An x-band interferometer measures the line density across the end fan. The line density is converted to density at the end wall using the 32 cm path length and the magnetic field ratio of 4.3.

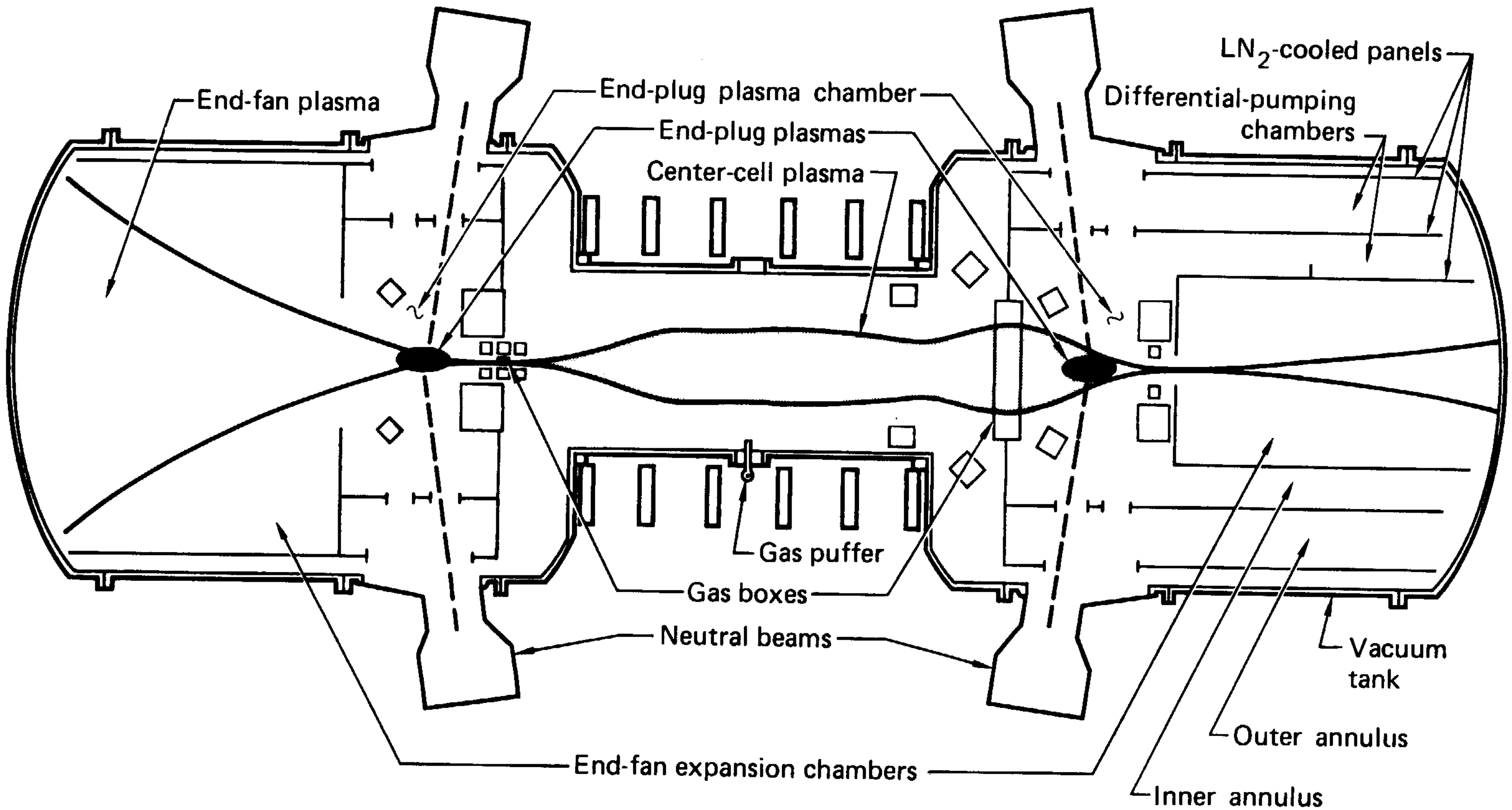

End-fan plasma
End-plug plasma chamber
End-plug plasmas
Center-cell plasma
LN_2-cooled panels
Differential-pumping chambers
Gas puffer
Gas boxes
Neutral beams
Vacuum tank
Outer annulus
Inner annulus
End-fan expansion chambers

Figure 1

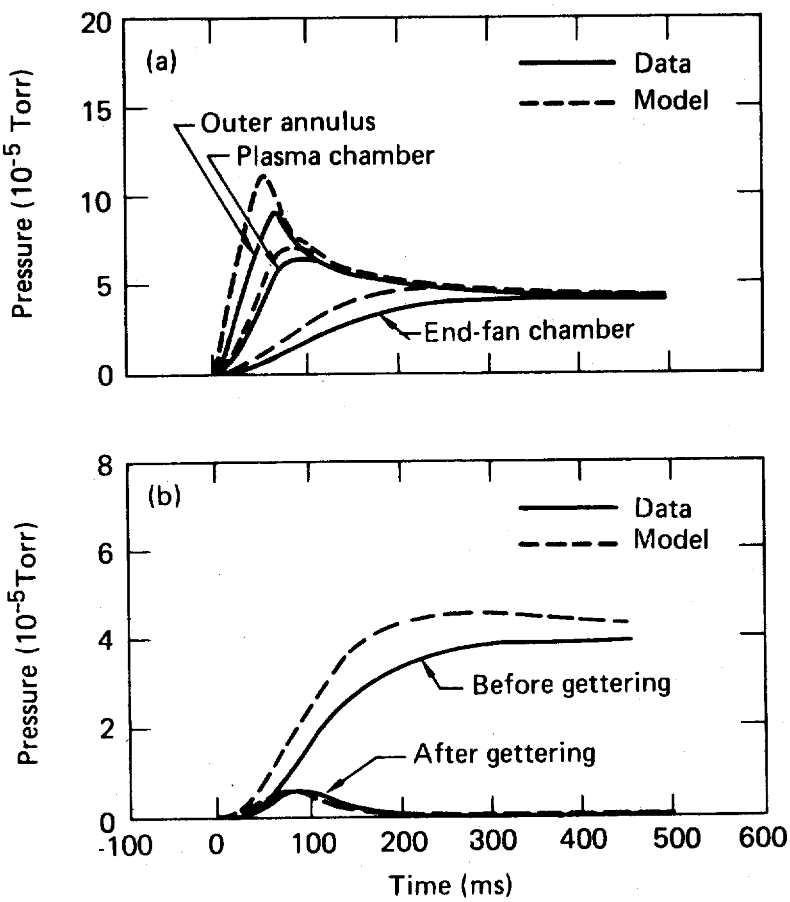
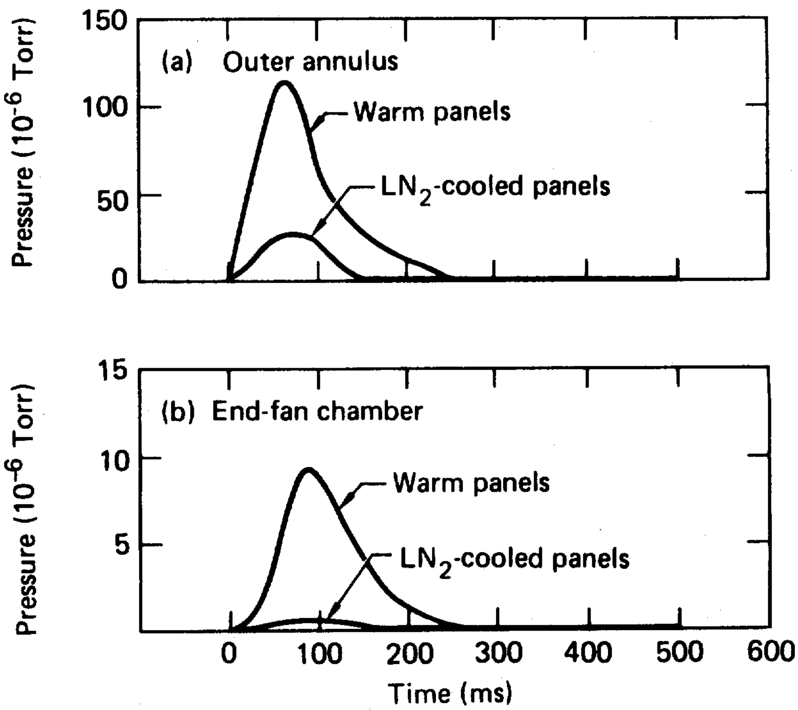

(a)
Data
Model
Outer annulus
Plasma chamber
End-fan chamber
Pressure (10^{-5} Torr)
20
15
10
5
0
(b)
Data
Model
Before gettering
After gettering
Pressure (10^{-5}Torr)
8
6
4
2
0
-100
0
100
200
300
400
500
600
Time (ms)

Figure 2



Pressure (10⁻⁶ Torr)
150
100
50
0
(a) Outer annulus
Warm panels
LN2-cooled panels
Pressure (10⁻⁶ Torr)
15
10
5
(b) End-fan chamber
Warm panels
LN2-cooled panels
0
100
200
300
400
500
600
Time (ms)

Figure 3

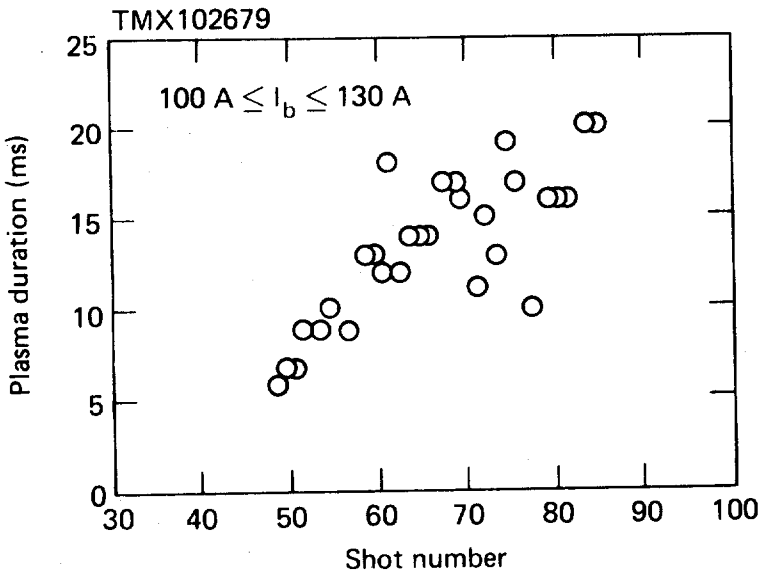

TMX102679
100 A ≤ I_b ≤ 130 A
Plasma duration (ms)
25
20
15
10
5
0
30
40
50
60
70
80
90
100
Shot number

Figure 4

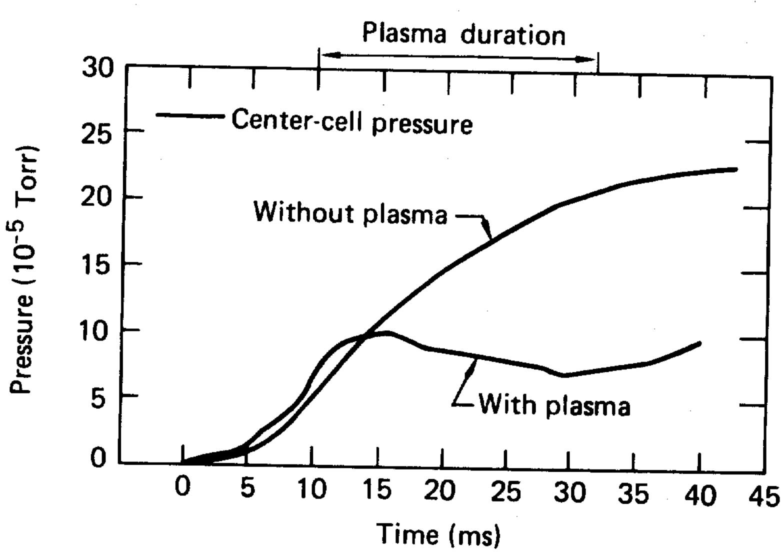

Plasma duration
Center-cell pressure
Without plasma
With plasma
Pressure (10^-5 Torr)
0
5
10
15
20
25
30
0
5
10
15
20
25
30
35
40
45
Time (ms)

Figure 5

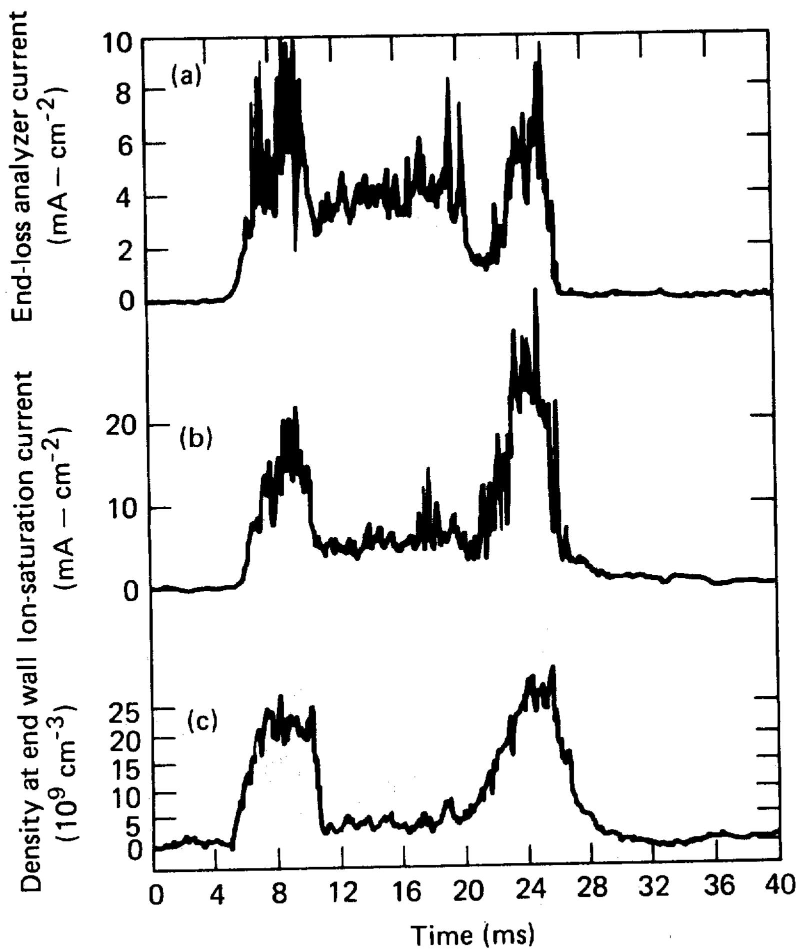

End-loss analyzer current
(mA – cm^{-2})
10
8
6
4
2
0
(a)
Ion-saturation current
(mA – cm^{-2})
20
10
0
(b)
Density at end wall
(10^{9} cm^{-3})
25
20
15
10
5
0
(c)
0
4
8
12
16
20
24
28
32
36
40
Time (ms)

Figure 6